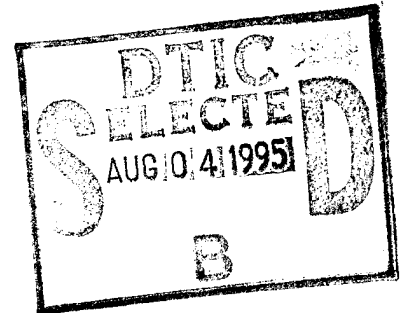# Experimental Evaluation of Three Dimensional Effects in Cracked Motor Grain Geometries

C. W. Smith

Virginia Polytechnic Institute and State University
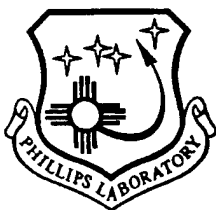ESM—VPISU
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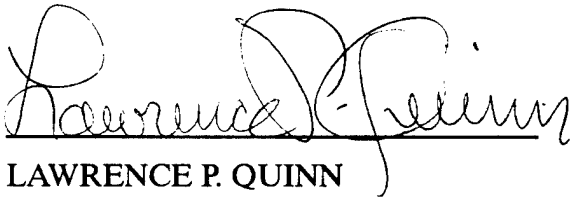
FOREWORD

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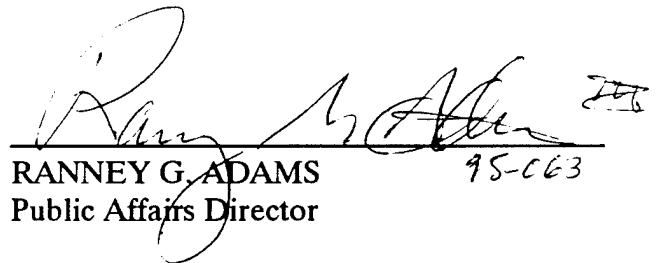
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13. ABSTRACT (MAXIMUM 200 WORDS)

A series of experiments utilizing a refined frozen stress photoelastic analysis were conducted on a generic motor grain geometry consisting of six equally spaced fins in order to study the feasibility of measuring crack growth and stress intensity factor (SIF) distribution along the grown flaw borders of internal surface cracks under internal pressure and corresponding corner singularity orders where the cracks intersected fin surfaces. Subsequently, these methods were applied to scale models of a real motor grain. Parallel studies using a coarse grid method were conducted on cracked inert propellant and pure binder biaxial models in order to study the influence of hard particles on crack opening and growth and to characterize the material behavior of simulated motor grain over an environmental range typical of transport and storage of rockets. Uncracked specimens were used to study stress relaxation and using acousto-ultrasonics, damage development was measured. Results showed that i) crack geometry and SIF distributions were generally three dimensional but, in special cases, could be predicted with simple two dimensional models, ii) near tip opening and growth mechanisms were the same in both pure binder and inert propellant but that a non-linear blunt-growth-blunt phenomenon, occurred at all temperatures except –65°F where the blunting was suppressed, simulating closely linear elastic fracture mechanics behavior, iii) measured corner singularity orders were comparable to theoretical results in the photoelastic models. In the simulated propellant models, displacement values were greater for blunted than for sharp crack tips, iv) damage accumulation was best described by an energy content parameter in the acousto-ultrasonic method.

14. SUBJECT TERMS

crack growth; motor grain geometries

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TABLE OF CONTENTS

1. Introduction

Improved performance requirements in rocket motors, especially those requiring longer storage life after transport place increasing importance upon the influence of motor grain defects. The most serious class of defects are cracks or flaws which may initiate during curing transport or later during storage. These cracks, if internal, alter the burning surface during firing and may significantly affect the motor performance.

Nearly all motor grain cracks are three dimensional as opposed to straight front through cracks, and their growth is often non-planar, leading to severe complications in mathematical modeling. Moreover, motor grain material is highly sensitive to the environmental effects and is a particulate composite, consisting of graded hard particles distributed in a rubber matrix. It has been established [1] however, that, when confined in a case, the material behaves in a pseudoelastic manner, and, as has been shown in tests under a separate contract (F04611-92-C-0011) [2] cracked specimens of real propellant exhibited classical brittle fracture as described by linear elastic fracture mechanics at or near the lower mil-spec temperature of -65°F. Since such fractures are the most critical, it is not inappropriate to employ an elastic method to study crack paths and stress intensity factor distributions along crack fronts in three dimensional (3D) problems and then attempt to simplify mathematical modeling of such problems based upon the data accumulated.

2. Program Objective

The objective of the program was to measure stress intensity factor (SIF) distributions, crack paths and corner singularity values and their effects on crack growth and fracture in motorgrain models under internal pressure loadings. In order to achieve these objectives, additional studies, facilitated through contract modifications, were conducted to establish the conditions under which homogeneous models reflect the response of the motor grain which is a particulate composite.

3. Program Scope

The program consisted of three phases:

Phase I - Development of a refined frozen stress method for obtaining the stress intensity factor distributions along the front of surface cracks emanating from the tips of fins of central openings in cylindrical photoelastic models. In addition, a grid method was developed under a contract modification to measure displacements and dominant eigenvalues in motor grain material models. Finally, also under a contract modification an acousto-ultrasonic technique was developed to study the damage accumulation in inert motor grain material under quasistatic loading.

Phase II - The refined frozen stress method was then used to extract optical data which were then converted into estimates of the stress intensity factor distribution along the flaw border using appropriate algorithms and also corner singularity orders in the cracked photoelastic motor grain models. A generic motor grain geometry consisting of a cylinder with an opening consisting of six equally spaced and identical fins was used to evaluate the method and resulting data. Subsequently, the method was applied to scale models of a real motor grain geometry consisting of unequal fin lengths. In parallel with this work and under contract modification, tests were conducted using the grid method on cracked biaxial specimens of pure binder and inert propellant in order to establish the near tip influence of the hard particles in the rubber matrix, measure the

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dominant eigenvalue and characterize the motor grain material behavior over a limited environmental range normally encountered during curing, transport and storage. Finally, damage growth was measured in the motor grain material using acousto-ultrasonics.

Phase III - A final technical report describing the results of the program.

4. <u>**Work Plan and Accomplishments**</u>

i) **Frozen Stress Studies**

Due to the rather extensive amount of data accumulated during the course of the project, it was decided to summarize the work and accomplishments by including a few of the reprints of papers published as a result of the study.

The first series of photoelastic experiments were directed towards shallow, moderate depth, and deep surface cracks emanating from the tip of one of six identical fins in the generic six finned motor grain model. The test procedures, methods of analysis and results are found in Attachment #1. As a result of these studies, which revealed a nearly uniform stress intensity distribution around the crack border, a simple model was developed for predicting the stress intensity factor at the point of maximum penetration of the flaw.

Moreover, using a stress type variable eigenvalue algorithm, values of the corner singularity where the flaws intersected the fin surface were found to agree closely with prior analysis.

Subsequent to the above tests on cracks, which remained planar and grew in the plane of symmetry of the fin with the crack, a second series of tests were conducted where the starter cracks were inclined to the plane of symmetry of the fin. When these cracks grew, their surfaces became non-planar and the stress intensity distribution magnitude depended strongly upon the location of the crack. The results of these studies are found in the middle part* of Attachment #2. It was found that the SIF distributions were

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* Section entitled "Summary of Results for Unsymmetric Cracks."

no longer uniform and that the value of the SIF at the midpoint of the crack front was either the maximum value or within experimental scatter of the maximum. The path of the crack front midpoint was found to closely follow a principal direction in the uncracked body and a two dimensional finite element model was constructed which yielded a close prediction to the actual crack path. All of the cracks in the generic model were symmetric with respect to their midpoints.

Having validated the frozen stress method for the generic model, the method of experimental analysis was then applied to scale models of an existing motor grain which had 8 fins of different lengths. These tests and their results are found in the latter part of Attachment #2**. These studies revealed a complex behavior when the crack mid-point turned from its initial path into a principal direction of the uncracked model and suggest a need for further studies of the turning effect. Significant variation in the SIF distributions were also observed.

ii) Material Characterization and Near Tip Behavior of Motor Grain Material.

In parallel with the frozen stress tests, under a contract modification, tests were conducted on cracked biaxial specimens of inert propellant and of pure binder using the grid method in order to assess the extent to which the presence of hard particles in the inert propellant would invalidate the application of fracture mechanics of single phase materials. Possible three dimensional effects were assessed with a three dimensional finite element model. Test procedures and results are found in Attachment #3. Results showed that, while the presence of hard particles promoted blunting near the crack tip, and led to a blunt-growth-blunt phenomenon of crack extension, the near tip mechanisms in the pure binder were the same but blunting was suppressed. The finite element model suggested that a straight through the thickness crack would generate reduction in the SIF values at void locations locally along the crack front with increases in adjacent regions but, on the average, crack advance would likely be uniform.

** Section entitled "Crack Growth Initiation in Scale Model of Motor Grain."

Under another contract modification, a test program was carried out on cracked biaxial motor grain material specimens in order to determine the near tip material response under the range of test environments to which motor grain might be subjected during transport and storage. In addition, relaxation properties were measured from uncracked biaxial specimens. The test procedures and results are described in Attachment #4. Results showed that time dependent effects were present over the entire range of test environments. However, at or near the lower mil-spec temperature of $-65°F.$, the material behaved as an elastic brittle material, and exhibited unstable crack growth resulting in brittle fracture over the entire range of head rates. Moreover, reasonable values were obtained for the dominant eigenvalue for sharp cracks at the surface using a continuum algorithm. Finally the material followed the Williams-Landel-Ferry equation over the limited range included in the tests.

Under a separate contract modification, an experimental study was undertaken to evaluate the potential of the acousto-ultrasonic technique for measuring the development of damage from voids in uncracked inert propellant. Test methods and results are described in Attachment #5. Results showed that the energy content parameter was effective in characterizing damage in the material. However, it was found that mechanisms contributing to the central frequency requires further investigation before such a claim can be made for central frequency.

5. Conclusions

From the frozen stress experiments, it can be concluded that:

i) Cracks emanating from a fin tip near or on the plane of symmetry of the fin will grow in that plane, being or becoming planar cracks. Their aspect ratio will change during crack growth to produce nearly uniform SIF distributions along the flaw borders. The SIF at maximum crack depth can be accurately estimated with a simplified two dimensional model.

ii) When cracks emanate from a point near the fin tip out of the plane of symmetry of the fin tip, the crack front mid-point turns towards a principal direction in the uncracked model and follows that direction. The SIF distribution is non-uniform and remains so during crack growth and the SIF intensity depends strongly on the crack location.

iii) In scale models of a motor grain with unequal fin lengths, the worst case crack location appears to be located a short distance from the relatively flat part of the long fin tip in the direction of a short fin (Fig. A2-11). When the initial crack began to turn toward a principal direction, a complex redistribution of the SIF resulted.

From the tests on cracked biaxial specimens of inert propellant under various test environments, it may be concluded that:

iv) The near tip mechanisms for the behavior during opening and growth is the same over the entire range of test environments studied. However, at or near the lower mil-spec temperature, the blunting which occurs during the highly non-linear blunt-growth-blunt process is suppressed so that crack growth appears to be continuous.

v) Dominant eigenvalues at the free surface were somewhat larger for blunted than for sharp tips as determined by a continuum single phase algorithm.

vi) Stress relaxation behavior of uncracked biaxial specimens followed the WLF Prediction within the range of test environments studied.

Finally the acousto-ultrasonic examination of inert propellant showed that the energy content parameter provided a reasonable representation of damage accumulation in uncracked specimens.

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[2] Smith, C.W., Mouille, H., and Liu, C.T., "Temperature, Rate and Gradation Effects on the Opening and Growth of Cracks in Particulate Composite Bodies," *Advances in Experimental Mechanics and Biometrics*, Jones, W.F. and Whitney, J.M., Eds., ASME AD-V29, AMD-V146, pp. 29–40, 1992.

Addendum:

In addition to attachments #1 through #5, the following publications include results obtained under Contract No. 4611-88-K-0025.

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3. Smith, C.W., "Effect of Near Tip Behaviour of Particulate Composites on Classical Fracture Concepts," *Recent Development in Composite Materials Structures*, American Society of Mechanical Engineers Aerospace Division, Vol. 19, Applied Mechanics Division, Vol. 113, November 1990, pp. 73–80.

4. Smith, C.W., Chang, C.W. and Wang, L., "Prediction of Stress Intensity Factors in Rocket Motor Geometries; Development of a Photoelastic Data Base," *Proc. of 1991 Spring Conference on Experimental Mechanics*, Milwaukee, WI, June 10–13, p. 565–571.

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9. Smith, C.W., Wang, L. and Tanaka, M., "Influence of Storage Environment Upon Crack Opening and Growth in a Particulate Composite," *Proc. of 50th Anniversaty Cont. of Society for Experimental Mechanics*, pp. 1014–1021, (June 1993).

10. Smith, C.W. and Liu, C.T., "Near Tip Behavior in a Particulate Composite Material- An Experimental and Analytical Investigation," *Proc. of 2nd International Conference on Computational Mechanics*, pp. 641–648, (1993).

11. Smith, C.W., Wang, L. and Liu, C.T., "Experimental Determination of Crack Growth and SIF Determination in Motor Grain Models," *Novel Experimental Techniques in Fracture Mechanics*, ASME AMD Vol. 176, pp. 101-112, December (1993).

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APPENDIX
Abstracts of Cited References

Prediction of Stress Intensity Factors in Rocket Motor Geometries; Development of a Photoelastic Data Base

Smith, C.W.

A series of frozen stress photoelastic experiments were conducted on a rocket motor grain geometry containing a natural surface flaw emanating from the tip of the finger of an internal star shaped central hole under internal pressure. Stress intensity distributions for shallow, moderate depth and deep cracks were obtained. Stress intensity distributions around the crack borders were found to be nearly uniform, suggesting the feasibility of two dimensional predictive analyses. The loss in the inverse square root singularity at the points of intersection of the crack border with the inner surface was approximately confirmed experimentally but appeared to have negligible effect upon the stress factor distribution.

APPENDIX
Abstracts of Cited References
cont.

Stress Intensity Distributions and Crack Growth Concepts for a Basic Motor Grain Shape With
Application to a Scaled Model Geometry

Smith, C.W., Wang, A.L., Liu, C.T.

A series of refined photoelastic stress freezing experiments were conducted on pre-cracked models of a basic motor grain shape. Stress intensity distributions and grown crack shapes obtained from cracks emanating from fin tips in a plane containing the axis of symmetry of the fin, together with cracks originating near the fin tip but inclined to the axis of symmetry of the fin are summarized. For those cracks inclined to the axis of symmetry, differences in growth paths and stress intensity distributions appeared to be strongly affected by the change in location and orientation of the crack surface at initiation of growth. This aspect of the problem was then studied on a scale model of an actual motor grain. Complex resulting behaviors are described.

Effects of Near Tip Behavior of Particulate Composites on Classical Concepts

Smith, C.W., Liu, C.T.

The principles of classical fracture mechanics, especially linear elastic fracture mechanics (LEFM) including small scale yielding are well established for single phase materials. In recent years, much development and use of polyphase (composite) materials has led to the application of fracture mechanics to such materials. In this paper, the effects of embedding hard particles in a soft matrix upon the opening, growth and stress intensity factor (SIF) of cracks in the particulate composite are studied from a combination of surface measurements and a "first cut" three dimensional finite element model, the latter for assessing the projection of the observed surface effects in the thickness direction.

APPENDIX
Abstracts of Cited References
cont.

Temperature, Rate and Gradation Effects on the Opening and Growth of Cracks in Particulate Composite Bodies

Smith, C.W., Mouille, H., Liu, C.T

The mechanical response of a particulate composite, whose composition and gradation is believed to closely simulate a solid propellant is studied at temperatures of −65°F, 72°F and 165°F and at test head rates of 2.54 and 12.70 mm/min., ranges normally encountered during handling and storage. After determining the approximate gradation, and biaxial tensile stress–strain and relaxation response of the material, experiments are conducted which focus upon the opening and growth of cracks in single edge cracked biaxial test specimens to determine near tip response. The grid method is employed to obtain near tip contours for local displacement and strain and continuum algorithms are employed to estimate dominant eigenvalues where the cracks intersect the free surface of the material. It is concluded that crack tip opening and growth mechanisms are qualitatively similar over the full range of temperatures and head rates. Furthermore, the head rate effect over the ranges studied is not significant. Moreover, while global response is significantly different at −65°F from the other two temperatures, results from tests at room temperature and 165°F are much less dissimilar. Finally, some success was met in measuring the dominant eigenvalue at the free surface using a continuum algorithm.

APPENDIX
Abstracts of Cited References
cont.

Acousto–Ultrasonic Technique Applied to the Assessment of Damage in Filled Polymers

Tang, B., Liu, C.T., Henneke, E.G.

Deformation and fracture of composite polymers such as solid rocket propellant depend upon the applied load or deformation history. The internal damage that accumulates as a result of loading evidences itself in such materials as a volume dilatation [1], which can be described in terms of microstructural damage processes such a dewetting, vacuole formation and growth, binder rupture, and so forth. For good composite polymers, the adhesive bond between the binder and the filler particles fails first, and then vacuoles form at the binder–filler interface, surrounding and engulfing the filler particle. Further straining results in the growth of the vacuoles and stretching of the binder. Otherwise, initial failure may occur in the binder material due to stress concentrations in the vicinity of the binder–filler interface. Development of vacuole growth and coalition will eventually form one or more macroscopic cracks, progressing to total specimen failure. Methods for quantifying such phenomena are essential in characterizing the material behavior.